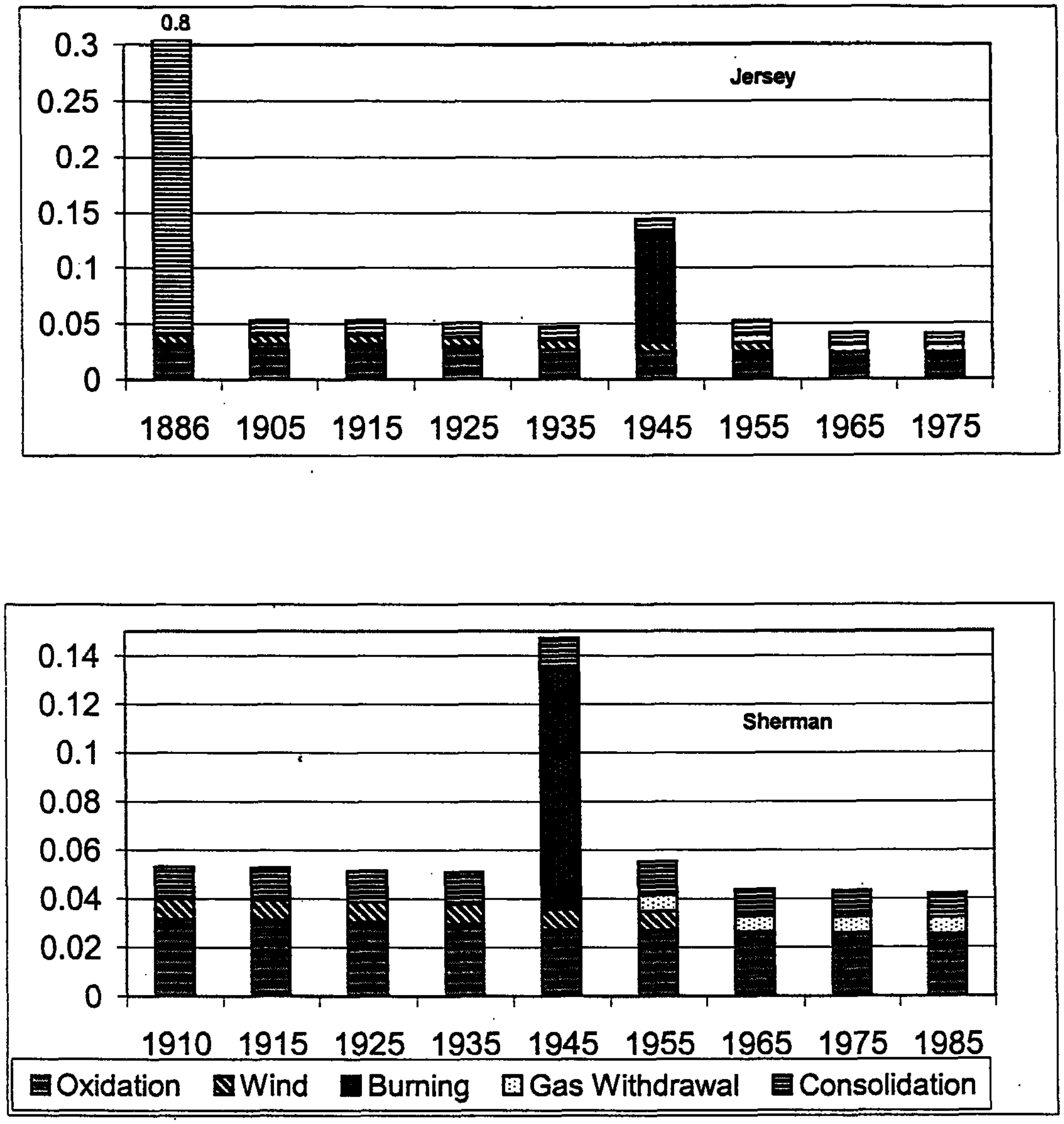
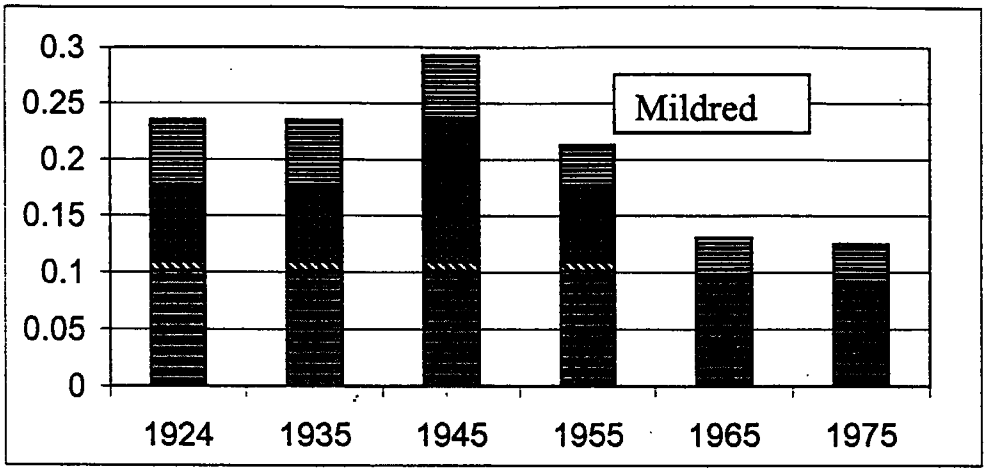
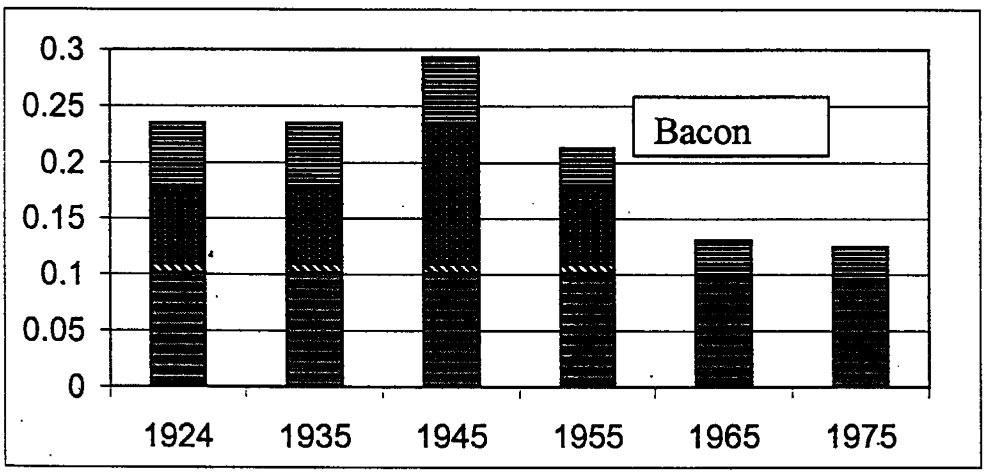
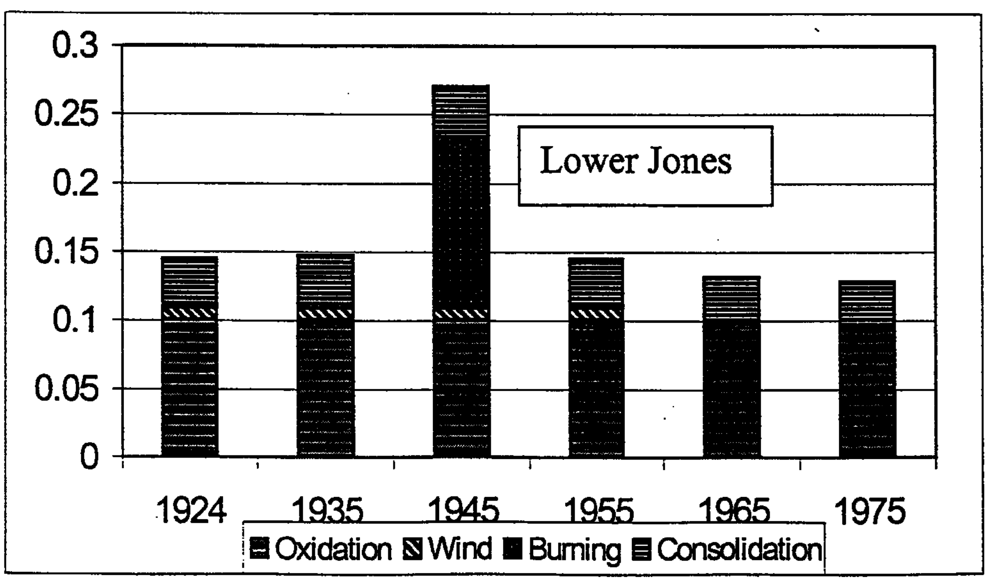
Figure 1. Subsidence rates in feet per year from 1886 to 1985 due to different causes for Jersey, Sherman, Bacon and Mildred Islands and Lower Jones Tract.




0.3
0.25
0.2
0.15
0.1
0.05
0
Mildred
1924
1935
1945
1955
1965
1975


0.3
0.25
0.2
0.15
0.1
0.05
0
Bacon
1924
1935
1945
1955
1965
1975


0.3
0.25
0.2
0.15
0.1
0.05
0
Lower Jones
1924
1935
1945
1955
1965
1975
Oxidation
Wind
Burning
Consolidation

4.2.2 Limitations in the Determination of the Causes of Subsidence

Although estimates of the magnitude of the causes of subsidence are consistent with what is known about the processes affecting subsidence in the Delta, the primary limitation of the analysis is the lack of explicit and deterministic simulation of the causes of subsidence. The equation for microbial oxidation is based on limited data and does not explicitly simulate the microbial decomposition of the different components of the soil organic carbon. Consolidation during initial drainage is empirically based. Also, ongoing consolidation of the organic soil after initial drainage is simulated to be the result of water loss only. There is probably a rearrangement of the soil fabric as subsidence and decomposition proceeds that is not currently quantifiable and is not included in the model. Burning of organic soils in the Delta was not well documented and simulation of burning is based on limited data discussed in Cosby (1941) and Weir (1950). The mechanics of wind erosion are also not explicitly modeled due to lack of data. These limitations, especially as related to the simulation of microbial oxidation and consolidation, point to the need for additional data collection and research for improved understanding and prediction of subsidence rates.

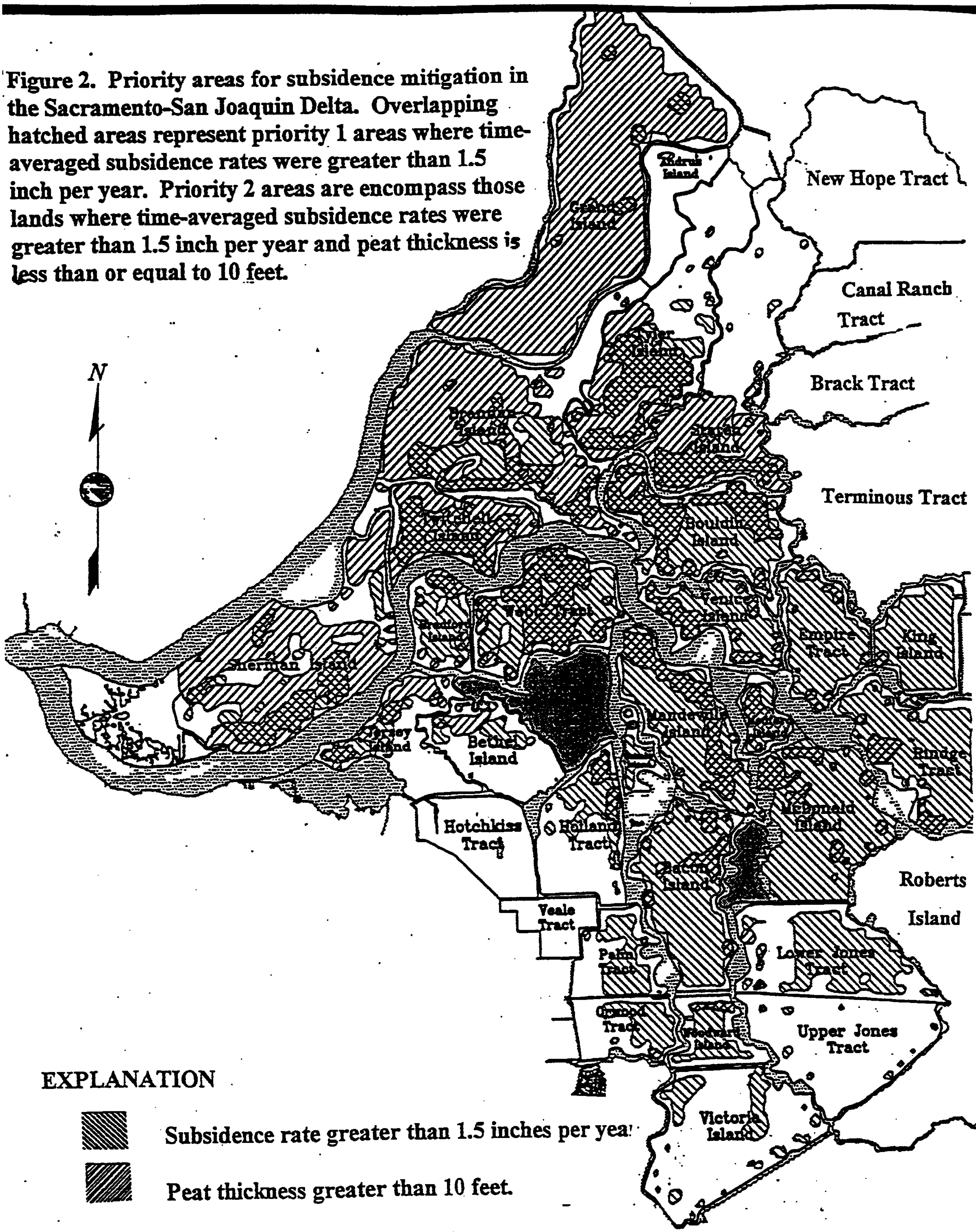
5.0 Distribution of Priority Areas for Subsidence Mitigation

Figure 2 shows the distribution of the two priority areas for subsidence mitigation. The priority 1 area is comprised of lands where the peat thickness is greater than 10 feet and the time-averaged subsidence rate was greater than 1.5 inch per year. The priority 2 area is comprised of lands where the time-averaged subsidence rate was greater than 1.5 inch per year and the peat thickness is 10 feet or less. Peat thickness is generally greatest in the western and northern parts of the Delta; the largest areas of peat thickness greater than 10 feet are on Sherman, Twitchell, Brannan-Andrus, Grand, Staten and Tyler islands and Webb Tract. The amount of area in priority 1 varies among these and other islands according to the distribution of time-averaged subsidence rates. The acres for the two priority areas for the different islands are presented in Appendix B.

The largest acreage for priority 1 is on Webb Tract in the west-central Delta. Venice, Bouldin and Mandeville islands in the central Delta also have large acreage assigned to the priority 1 area. Twitchell, Brannan-Andrus and Sherman islands and Webb Tract in the western and west-central Delta and Tyler Island in the northern Delta also have large areas in this priority. Although Grand Island has a large acreage of peat thicker than 10 feet, the time averaged subsidence rates are almost all less than 1.5 inch per year. The total area for priority 1 is about 22,900 acres.

The islands with the largest acreage in the priority 2 area are in the central Delta where subsidence rates have been historically high and there are large areas of peat that are less than 10 feet thick. MacDonald, Bacon and Mandeville islands and Empire Tract in the Central Delta and Rindge Tract in east-central Delta and Webb Tract in the west-central Delta have large areas in priority 2. Other central Delta islands (Lower Jones Tract, Bouldin Island and Venice Island) have substantial areas in priority 2. The islands and tracts of the western and northern Delta generally have low acreage in the priority 2 area

Figure 2. Priority areas for subsidence mitigation in the Sacramento-San Joaquin Delta. Overlapping hatched areas represent priority 1 areas where time-averaged subsidence rates were greater than 1.5 inch per year. Priority 2 areas are encompass those lands where time-averaged subsidence rates were greater than 1.5 inch per year and peat thickness is less than or equal to 10 feet.



EXPLANATION

Subsidence rate greater than 1.5 inches per yea

Peat thickness greater than 10 feet.

because of the relatively low time-averaged subsidence rates. The total area for priority 2 is about 35,700 acres. The total area for priorities 1 and 2 is about 58,600 acres.

Deverel and others (1998) reported that time-averaged subsidence rates were highly correlated with percent soil organic matter on Sherman Island. The distribution of soil organic matter content in the Delta generally reflects the distribution of subsidence rates shown in Figure 2. For example, the highest organic matter contents (greater than 30 percent) are in the central, east-central and the west-central Delta (Twitchell Island, Bradford Island, Webb Tract, Bouldin Island, Venice Island, Empire Tract, Rindge Tract, King Island, Bacon Island, Lower Jones Tract). The time-averaged subsidence rate for the majority of these islands is greater than 1.5 inch per year (Figure 2). Islands where organic matter contents are generally lower than 15 and 30 percent such as Sherman Island, Brannan-Andrus Island, Staten Island and Victoria Island are generally at the periphery of the Delta. The subsidence rates on these islands are generally less than 1.5 inch per year.

5.1 Uncertainty in the Delineation of Priority Areas

The primary uncertainties in the spatial analysis are the result of uncertainties in the thickness of the peat soil and the error in the estimation of the subsidence rate. The subsidence rate error is the result of errors associated with the use of topographic elevations as described above and the use of different datums for the 2 surveys for the topographic maps published in 1906 to 1911 and 1976 to 1978. In general, large errors in the subsidence rates correspond to areas of the lowest time-averaged subsidence rates. The error in the subsidence rate estimate due to the mapping error is 50 percent or less for much of the Delta where there are peat deposits. The error in the subsidence rate generally increases approaching the periphery of the Delta. The error in the western, eastern, southern and northern edges of the Delta generally approaches or exceeds 100 percent.

The key questions related to the error for the purpose of determining the priority areas based on time-averaged subsidence rates are: 1) Is the distribution of subsidence rates consistent with what is known about the distribution of present-day subsidence rates? and 2) What is the error associated with assignment of areas to one of the two categories (less than and greater than 1.5 inch per year) for subsidence rates?

The first question can be answered qualitatively based on recently collected data for subsidence for selected areas of the Delta. Specifically, data from Rojstaczer and Deverel (1995), Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) are consistent with the spatial distribution of subsidence rates presented here. Time-averaged subsidence rates reported for the central Delta (Lower Jones Track, Bacon and Mildred islands) are greater than in the western Delta (Sherman and Jersey islands) (Rojstaczer and others, 1991). However, subsidence has not been measured extensively throughout the Delta so that it is impossible to compare rates for all the islands. The subsidence rates in Figure 2 are generally consistent with what is known about subsidence and organic soils in the Delta (Prokopovitch, 1985). The highest soil organic matter contents and subsidence rates are in the central Delta. The soils are lower in organic matter content and subsidence rates are lower approaching the margins of the Delta

The second question can be answered based on the distribution of error for subsidence rates. The error analysis is discussed in Appendix B. Data for Sherman Island and Webb Tract were used to evaluate the effect of errors on the acreage within each priority area. The data for these islands represent the variability in the data set and the error analysis illustrates the possible range in calculated acreage in the two priority areas.

The range of acreage on Webb Tract for priority 1 shows that the acreage in priority 1 could be overestimated by 54 % and underestimated by less than 1 %. For priority 2, the range in acreage on Webb Tract shows that the acreage in priority 2 could be overestimated by 24 % and underestimated by 10%. In contrast, the ranges of acreage in each priority for Sherman Island are large, ranging up to 1,000 percent. The time-averaged subsidence rates for Sherman were lower than Webb and therefore the error associated with the subsidence-rate estimate is higher and the range of acreage classified in each priority area is large. The results of this analysis point to a need for additional data collection for subsidence rates, especially in the western Delta.

The areal distribution of the estimation error for the peat thickness was not determined. The density of borehole data and the error in the land-surface elevation primarily determines the error. The land-surface elevation error is due to leveling error in the determination of land-surface elevation that is about plus or minus 2.5 feet and the subsidence that has occurred since 1974 (about 1 to 4 feet). The total land-surface elevation error ranges from about –1.5 to 6.5 feet.

Appendix B shows and discusses the number and average density of data points for borehole logs used to estimate the peat thickness. In general, data densities greater than 200 acres per data point result in moderate to high uncertainty in the estimation of the basal peat elevation for large areas of the islands. Of those islands where the density of peat thickness data is greater than 200 acres per data point, only 7 have acreage in the 2 priorities (Orwood Tract, Victoria Island, Brannan and Andrus islands, King Tract, Tyler Island and Grand Island). Brannan-Andrus Island, King Tract and Tyler Island have significant acreage in the 2 priorities. Grand Island is mapped as having a large area of thick peat but has little acreage in priority area 1 because of the low time-averaged subsidence rates. The percent organic matter in the soils on Grand Island is relatively low. Although there is uncertainty in the delineation of the priority areas for subsidence mitigation, the delineation is based on the available data and provides a starting point for further data collection efforts to better define areas and management practices for subsidence mitigation.

6.0 Land- and Water Management Practices for Subsidence Mitigation

The primary factor contributing to present-day subsidence in the Delta is microbial oxidation of soil organic carbon. The oxidation of soil organic carbon is directly proportional to soil temperature and decreases with increasing soil moisture (Deverel and Rojstaczer, 1996). The results of studies conducted by the US Geological Survey and

Department of Water Resources (Deverel and others, 1998) demonstrated that permanent shallow flooding reversed the effects of subsidence on Twitchell Island. Permanent shallow (about 1 foot) flooding resulted in a net carbon accumulation and accretion of biomass. The plots were first flooded in February 1993. Cattails were the primary species that colonized the plots. During 1993, the cattails covered about 25 percent of the plot. In 1994, 30 to 55 percent of the plot was covered and full vegetative cover was achieved in 1995. Cores were collected in the flooded plot while it was temporarily drained in July 1997. The results of the coring showed that about 3 to 6 inches of firm biomass accreted from 1993 to 1997 during 2 years of growth under full vegetative cover and 2 years of growth under partial cover. Other water-management strategies that were evaluated; seasonal flooding during the late fall and winter with and without irrigation during the spring and summer, resulted in a net carbon loss and are not viable mitigation strategies for stopping subsidence. This is due to large microbial oxidation rates that occur during the spring and summer.

Consistent with the potential of permanent shallow flooding to reverse the effects of subsidence, two projects are funded and one is underway to evaluate the large scale effects of this management practice. First, data collection began in October of 1997 on Twitchell Island on a 15-acres demonstration project for increasing land-surface elevation through biomass accumulation under permanently flooded conditions. The overall approach is to verify the reversal of subsidence in organic soils under permanently flooded conditions at a larger scale than used in previous research (Deverel and others, 1998). The demonstration project will provide information about: 1) the large scale effects of permanent flooding on the carbon balance and land-surface elevation changes; 2) the effects of different water-management practices and vegetation on biomass accumulation and land-surface-elevation changes; 3) the effects of varying soil organic matter content on the carbon balance under permanently flooded conditions and 4) future potential increases in land-surface elevation.

Second, a $3.5 million project has been funded through the CALFED Category 3 process to develop quantitative answers to the key unanswered questions about the reversal of the effects of subsidence and the development of tidal wetland habitat in the Sacramento-San Joaquin Delta. The focus of the project is the development of cost-effective techniques for the reversal of the effects of subsidence. This will be accomplished through research and a demonstration project for tidal wetland habitat restoration on Twitchell Island that will be transferable to other Delta islands. Quantitative answers to questions about the feasibility of depositing sediment on Delta islands and potential water quality impacts of accreting the land surface through biomass accumulation will be addressed during the conduct of this project. This project is scheduled to begin in early 1999.

Other water- and land-management strategies are being evaluated that may stop, or reverse the effects of, subsidence include capping the organic soil with mineral material and reverse wetland flooding. Preliminary results by the USGS (Lauren Hastings, USGS, personal communication, 1998) indicate that capping the unsaturated peat soil with 2 feet of dredge sand reduces the emission of carbon dioxide by about 35%. Capping of partially saturated soil reduced emission of carbon dioxide by 23%. Capping saturated peat soil with dredge material could provide upland habitat in shallow flooded wetlands. Capping of the peat reduces the transport of oxygen and carbon dioxide in and out of the soil causing the rate of carbon dioxide emission to decrease.

Reverse wetland flooding involves shallow flooding during the spring and summer and drainage during the fall and winter. This may reduce oxidation when it is usually the greatest and result in organic matter accumulation. The USGS is currently evaluating this as a subsidence mitigation strategy.

Subsidence mitigation efforts should be coordinated with efforts to restore the ecological health of the Delta. From an ecological perspective, there needs to be freshwater wetlands covering the full range of ecosystem gradients in the Delta. To achieve this range, elevations on western Delta islands must be restored to bring some of the islands back into tidal circulation (Steve Johnson, The Nature Conservancy, 1997).

7.0 Summary and Recommendations

7.1 Summary

- A computer model was used to integrate and synthesize the available data for the historic causes of subsidence in Delta organic soils. The model that simulated the relative magnitude of the causes of subsidence was validated using measured data for carbon fluxes and subsidence rates on Sherman, Jersey, Bacon, and Mildred Islands and Lower Jones Tract.
- The model simulations indicate that 29 to 55 percent of the total amount of historical subsidence on the Delta organic soils that occurred from the late 1800's through the 1970's was due to microbial oxidation of organic carbon.
- The model simulations indicate that consolidation and shrinkage, whether initially or over time because of drainage, accounted for about 22 to 29 percent of the total historical subsidence. Burning has accounted for 9 to 24 percent of the total historical subsidence. Wind erosion has historically accounted for 3 to 34 percent. Gas withdrawal has historically accounted for less than 3 percent.
- Present-day subsidence is caused primarily by the microbial oxidation of organic carbon.
- Time-averaged subsidence rates and peat-thickness were used to determine priority areas for subsidence mitigation in the Sacramento-San Joaquin Delta.
- Two priority areas for subsidence mitigation were determined as follows. The priority 1 area encompasses lands where time-averaged subsidence rates were greater than 1.5 inch per year and peat thickness was greater than 10 feet. The priority 2 area encompasses lands where the subsidence rates were greater than 1.5 inch per year and the peat is less than or equal to 10 feet thick.
- The largest priority-1 areas are in the western, west central and central Delta. The total area for priority 1 is about 22,900 acres.
- The largest priority 2 areas in are in the central Delta and central-eastern Delta where subsidence rates have been historically high. The islands and tracts of the western and northern Delta generally have low acreage in priority 2 because of the low

historical subsidence rates in these areas. The total priority-2 area is about 35,700 acres.

- The total area for both priorities is about 58,600 acres.
- The uncertainty in the estimation of priorities depends on the magnitude of the time-averaged subsidence rate and the uncertainty in the estimation of the peat thickness. The error in the subsidence rate estimate is generally less than 50 percent where subsidence rates are greater than 1.5 inch per year. This primarily corresponds to areas in the central Delta. The error in the subsidence rate increases approaching the margins of the Delta.
- The error in the subsidence rate has relatively less effect in the assignment of priorities on islands where the time-averaged subsidence rates were high such as Webb Tract. However, it has a large effect on the assignment of priorities for islands such as Sherman where historical subsidence rates have been lower.
- Permanent and shallow flooding of organic soils and capping, reduce or stop subsidence rates and shallow flooding can stop or reverse of the effects of subsidence.
- The effects of continued subsidence include levee instability, increased seepage onto islands and water quality effects related to seepage and flooding.

7.2 Recommendations for Research and Additional Data Collection

Eight western Delta islands (Sherman, Jersey, Twitchell, Bradford, Holland, Hotchkiss, Bethel and Webb) encompass a key area for subsidence mitigation because of the potential for water quality deterioration as the result of a levee break on these islands during low flow. Figure 2 shows that large areas of Twitchell, Webb and Bradford are included in the first priority area. Relatively small areas of Sherman, Jersey, Bethel, Hotchkiss and Holland are included in the two priorities. However, the error analysis discussed above indicates that the uncertainty in the assignment of priority areas on Sherman Island is as large as 1,000 percent. The uncertainty on Webb Tract is small. Examination of the subsidence rates and the error in the subsidence rates for Jersey, Holland, Hotckiss and Bethel indicate that the error in the assignment of priorities for these islands is generally similar to the error for Sherman Island.

The uncertainty in the assignment of priorities points to the need for additional data for subsidence rates throughout the Delta prior to implementation of subsidence mitigation measures. Since subsidence mitigation is critical in the western Delta yet the uncertainty in the time-averaged subsidence rates can be high, additional data about the distribution of subsidence rates is recommended in the western Delta for a higher level of certainty for the implementation of subsidence control measures. Also, analysis by Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) demonstrate that subsidence rates are decreasing with time. Therefore, the present-day subsidence rates are lower than those reported here and additional information is required to refine the delineation of priority areas based on present-day subsidence rates.

Uncertainty in the basal peat elevations and current elevations in the Delta also point to the need for additional data. Because the most recent topographic leveling in the Delta was completed in the 1970's, the peat thickness data presented here are about 20 years old. These peat thickness data could be in error by as much as 6.5 feet because of subsidence that has occurred over the past 20 years. The peat thickness values are also uncertain for several islands as discussed above where data is sparse or lacking.

The effects of future subsidence on Delta levee stability have not been studied. Seepage and deformation are key processes that may be affected as the result of future subsidence. The area adjacent to the levee where levee stability is affected by subsidence and the time frame associated with this zone of influence needs to be determined through general and site specific analysis. Analysis should be conducted to determine the effects of future subsidence on levee deformation for different environments where the thickness of the peat and subsidence rates vary. Similarly, seepage analysis should be used to estimate volumes of seepage and the effects on levees for different subsurface materials, varying subsidence rates and different drain configurations.

Specific recommendations for future data collection efforts are as follows.

- Refine the delineation of priority areas by reducing the errors in subsidence rate estimates and peat thickness and determining present-day subsidence rates.
- Collect data for present-day subsidence rates and predict future subsidence rates. Present-day subsidence rates can be determined by measuring land-surface elevations in areas where there is historical data such as Mildred, Lower Jones and Bacon and determining land-surface elevations throughout the Delta at regular intervals. In the short-term, determination of soil organic carbon throughout the Delta in combination with measurement of land-surface elevations on selected islands will improve the delineation of priority areas.
- Future subsidence rates can be predicted by collecting data that will give more precision to the calculation of microbial oxidation described in this report. The evaluation and estimation of consolidation also require more data and analysis.
- Collect data for peat thickness. This can be done using geophysical methods or by determining land surface elevations and calculating the peat thickness using well-log data.
- Determine the effects of future subsidence on levee deformation and seepage.
- Continue to support development and pilot- and large-scale implementation of land- and water-management practices for subsidence mitigation.
- Integrate subsidence mitigation efforts with ecosystem restoration efforts.

APPENDIX A. DESCRIPTION OF COMPUTER MODEL FOR ESTIMATING THE RELATIVE MAGNITUDE OF THE CAUSES OF SUBSIDENCE AND MODEL RESULTS

A.1 Microbial Oxidation

The carbon flux data for Jersey Island collected from 1990 to 1992 (Deverel and Rojstaczer, 1996) was used to approximate the relation of microbial oxidation of organic carbon to soil organic carbon content. This relation was used to simulate subsidence due to microbial oxidation for Jersey Island at the study location of Deverel and Rojstaczer (1996). The mass of carbon lost by microbial oxidation was assumed to follow Michaelis-Menton kinetics (Conn and Stumpf, 1976):

$$CFLUX = (CFLUXMAX \times foc)/(Km - foc) \tag{A.1}$$

where
CFLUX = CO_2 loss from the soil in grams carbon cm^{-2} yr^{-1} due to microbial oxidation of organic carbon in the peat soil.
CFLUXMAX= maximum CO_2 loss from the soil in grams carbon cm^{-2} yr^{-1}
Km = Michealis-Menton constant, and
foc = the fraction of organic carbon in the soil in grams carbon per g soil

The values of CFLUXMAX and Km were determined from annual averages of monthly carbon flux measurements for two sites on Jersey Island where soil organic matter content values of 0.28 and 0.22 were measured (Deverel and Rojstaczer, 1996). The foc values were estimated to be one-half of the soil organic matter content for the sites on Jersey and other sites in the Delta as per Broadbent (1960). The average annual soil temperature and depth of the groundwater at these two sites were nearly identical during the period of measurement (1990 - 1992). These two data points were used to develop a linear plot of the reciprocal of CFLUX versus the reciprocal of the foc. The slope of this plot is equal to Km/CFLUXMAX and the intercept is equal to 1/CFLUXMAX. For each year of model simulation, CFLUX was recalculated based on the change in foc as the result of the change in soil carbon during the previous time step. The change in land surface elevation due to oxidation was estimated by dividing the annual carbon flux by the soil bulk density and the foc.

The parameters for equation A.1 developed from the Jersey Island data were used to simulate microbial oxidation on Sherman Island. For the central Delta Islands, Mildred and Bacon islands and Lower Jones Tract, the elevation data for Mildred Island in Rojstaczer and others (1991) was used to determine the parameters for equation 2.1. The parameters were determined by model calibration against elevation measurements determined from 1924 through 1981 (Weir, 1950; Rojstaczer and others, 1991). The values for CFLUXMAX and Km determined for the Mildred Island calibration were then used to simulate land surface elevation changes for Lower Jones Tract and Bacon Island. Additional information about subsidence due to consolidation, wind erosion, burning, and withdrawal of natural gas and groundwater was also incorporated into the model.

A.2 Consolidation and Shrinkage

The amount of initial shrinkage and consolidation during reclamation was estimated from an empirical equation presented in Eggelsmann and others (1990) in which the consolidation is expressed as a function of the initial drainage depth in meters:

$$Consolidation = a \times (0.08 \times T - 0.066) \qquad \text{(A.2)}$$

where a is and empirical constant that is dependent on the degree of decomposition and texture of the peat, and T is the depth of initial drainage (assumed to be 6 feet).

Equation A.2 was used to estimate the total amount of consolidation due to initial drainage and was applied only once during simulation of subsidence for Jersey and Mildred islands. The empirical constant was assumed to have a value of 1.9 based on information presented in Eggelsmann and others (1990). For comparison, the amount of consolidation during initial drainage was also calculated using the drainage curves reported by Hanson and Carlton (1980). The results using the drainage curves were about 13 percent greater than those in which the Eggelsmann and others' (1990) equation was used.

A.3 Wind Erosion

Wind erosion of peat soils caused dust storms that affected Stockton, Lodi and Tracy prior to the early 1960's (Alan Carlton, former University of California Extenstion Specialist, personal communication, 1997). The prevailing westerly winds of oceanic air masses moving to the Central Valley caused dust storms primarily during May and June when wind speeds exceeded 15 miles per hour at a height of about 6 feet (Schultz and Carlton, 1959; Schultz and others, 1963). Carlton and Schultz (1956 – 1966) conducted experiments to determine the frequency and duration of dust storms caused by wind erosion of peat soils and methods for reducing wind erosion. Asparagus fields were a primary source of wind-eroded soil as the soil surface was mostly bare during May and June.

The Department of Water Resources (1980) reported values ranging from 0.1 inch per year based on personal communication from Alan Carlton to 0.25 to 0.5 inch per year from Weir (1950). Weir (1950) made no measurements of wind erosion and stated that "it may be as much as 0.25 to 0.5 inch per year." Carlton (1965) estimated wind erosion on Terminous Tract to be 0.57 inch per year from 1927 to 1957. This estimate was based on the elevation difference between a plot of land owned by Southern Pacific Railroad which was not farmed or cultivated but was surrounded by cultivated cropland. It is unclear whether the Southern Pacific Railroad land had been burned.

Crop histories in Thompson (1957) and the Weir transect notes (see Rojstaczer and others, 1991) were examined to determine the spatial distribution of crops grown on the islands where land surface elevation changes were simulated. Wind erosion was calculated at varying rates of 0.1 to 0.57 inch per year where asparagus was grown or where the land was fallow. There was generally a shift from the planting of asparagus and other vegetable crops to corn in the Delta in the 1950's and 1960's and the model calculated minimal wind erosion after 1965.

A.4 Burning

Weir (1950) and Cosby (1941) estimated that the peat soils were burned once every 5 to 10 years. Burning probably occurred more frequently during World War II when potatoes were grown extensively (Rojstaczer and others, 1991). Burning was used to control weeds and diseases and to create ash for potatoes. Weir (1950) stated that 3 to 5 inches of peat was lost during burning. Burning was simulated differently for the islands depending on the distribution of crops.

It was assumed that most of the Delta organic soils were planted to potatoes from 1938 to 1945. Elevation loss on all five islands due to burning was simulated to be 4 inches per burning during 2.5 burnings during this time period. Individual cropping patterns were used to simulate burning during other time periods for Mildred and Bacon islands. Potatoes were grown on Mildred Island from 1930-1938 and 6 inches of soil loss during 1.5 burning was simulated during this time period. Potatoes were also a predominant crop on Bacon from 1930 to 1938 and 1945 to 1955 and 6 inches of soil loss during 1.5 burning was simulated during each of these time periods. Alan Carlton (former University of California Extension Specialist, personal communication, 1997) stated that there was no burning in the Delta after 1955.

A.5 Withdrawal of Natural Gas and Groundwater

To determine the subsidence due to natural gas withdrawal, sediment cores collected from channel islands were dated by determining the levels of cesium-137 at 1-inch depth intervals (Rojstaczer and others, 1991). The surface elevation of channel islands has remained at sea level since the 1850's even though sea level rose about 0.08 inches per year indicating that sediment has been deposited on these islands. The peak fallout of ceisum-137 occurred in 1963 and was identified 3 to 7 inches below the sediment surface in cores collected on channel islands adjacent to Twitchell, Bradford and Bethel islands and Webb Tract, indicating that the channel islands subsided since 1963.

From 1963 to 1988 when the cores were collected, sea level rose about 2 inches. Therefore, the amount of subsidence due to gas withdrawal was between 0.04 and 0.2 inches per year ((3 – 2 inches) divided by (1988-1963)) = 0.04 inch/year, ((7- 2 inches) divided by (1988-1963) = 0.2 inches/year)). For modeling of subsidence, 0.08 inch per year of subsidence as the result of gas withdrawal was estimated for Jersey Island based on the results of ceisum-137 results reported in Rojstaczer and others (1991) for the channel island adjacent to Bradford Island. Subsidence due to gas withdrawal was not simulated for the Sherman, Mildred and Bacon islands or Lower Jones Tract because elevation changes along the Weir transect were compared to a benchmark and structures that was also affected by these withdrawals. Records from the California Department of

Conservation, Division of Oil and Gas, indicate that gas production began to increase substantially in the mid-1950's and gas withdrawal was simulated as a contributor to subsidence in the model after 1955.

A.6 Simulation of Total Subsidence

The total annual depth of subsidence was estimated by summing the depths of subsidence due to the different causes. The model accreted the land surface as it progressed backward in time based on the mathematical representation of the processes described above. The foc and bulk density were estimated for the most recent elevation data and time step and were recalculated for each subsequent time step. For Sherman and Jersey Islands, the initial foc and bulk density were from Deverel and Rojstaczer (1996). For Mildred and Bacon islands and Lower Jones Tract the foc was estimated from the soil survey for San Joaquin County (Soil Conversation Service, 1992) to be 0.25. The bulk density for the surface (0 to 2 feet) soils for Mildred, Bacon and Lower Jones was estimated at 0.74 g/cm^3 from the relation for data for organic matter content and bulk density collected on Rindge and Empire tracts and Bouldin Island reported in Hanson and Carlton (1980). A regression equation ($r^2 = 0.50$) was fit to the all the data of the form.

$$\textit{log bulk density} = 0.058 - 0.76 \times \textit{foc}. \qquad \text{(A.3)}$$

This equation was also used to estimate the bulk density at the beginning of each time step.

Subsidence and the microbial oxidation of organic carbon were simulated as a two-layer process based on data collected by Carlton (1966). The depth of soil affected by subsidence was assumed to be 5 feet. Carlton (1966) measured the depth of subsidence occurring in different layers on Venice Island from 1962 to 1966. Eighty-one percent of the total subsidence occurred in the upper 2 feet of the soil profile. Therefore, eighty-one percent of the organic carbon oxidation was simulated to occur in the upper 2 feet of the soil profile. The remainder was simulated to occur in the lower 3 feet. The foc was recalculated for each layer at each time step based on the change in the total mass of carbon for each layer. The final foc for the most recent and initial time step for the model for the lower layer was estimated at 0.375 based on information in Deverel (1983). The new oxidation rate was calculated for subsequent time steps using equation 2.1. The foc was not allowed to exceed 0.40 for either layer.

A.7 Model Results

Figure A.1 shows that there is good agreement between measured and modeled values for land-surface elevation changes for Bacon, Mildred and Lower Jones.

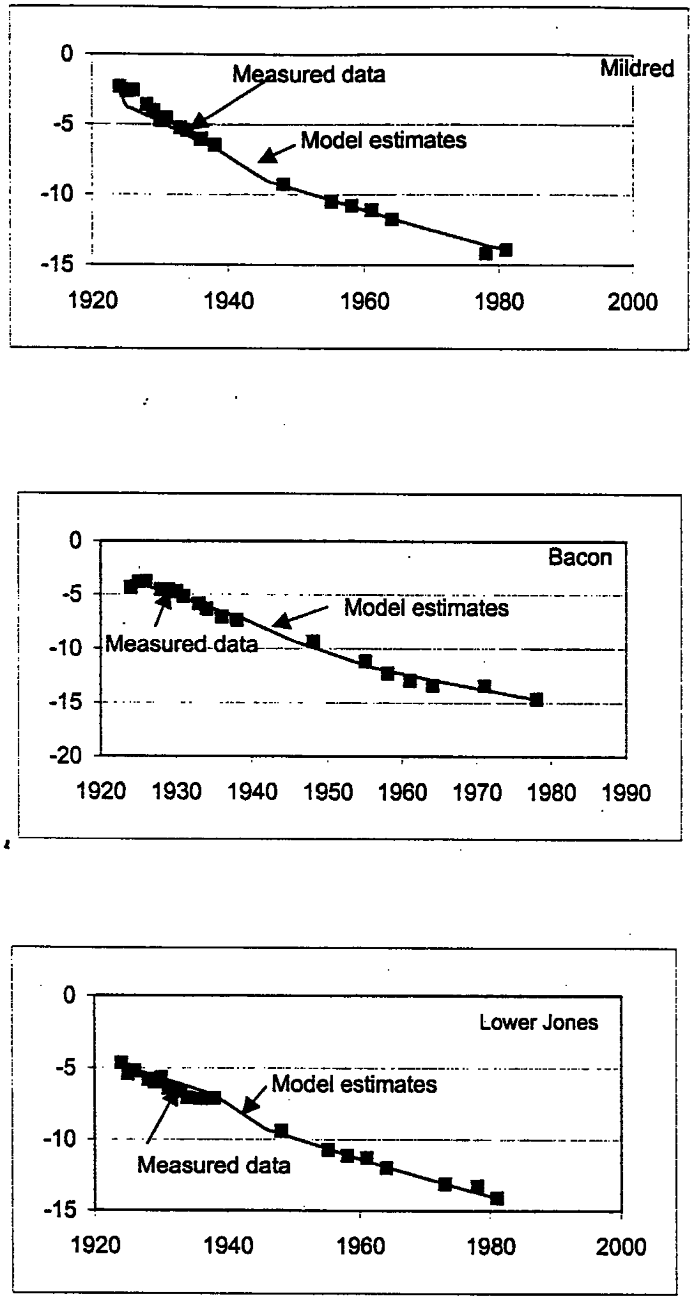


Figure A.1 Measured and model estimates for elevation changes for Mildred, Bacon and Lower Jones from 1924 to 1981. Squares represent measured data and solid lines represent model estimates. Elevation changes on the vertical axis are in feet above sea level.

APPENDIX B. METHODOLOGY, RESULTS, AND UNCERTAINTY ANALYSIS FOR THE DELINEATION OF PRIORITY AREAS FOR SUBSIDENCE MITIGATION.

A Geographic Information System developed by and housed at the Department of Water Resources Central District was used to delineate priority areas for subsidence mitigation based on time-averaged subsidence rates and peat thickness. The following describes the methodology, data, results and error analysis.

B.1 Determination of Areal Variability of Time-averaged Subsidence Rates

Two sets of US Geological Survey topographic maps were used to estimate the time-averaged rates of subsidence throughout the Delta from the early 1900's to 1976 through 1978. Specifically, topographic maps for the 1906-1911 mapping of the Delta at 1:31,680 scale were used to estimate land surface elevation on a 500-meter grid. The 1976 to 1978, 1:24,000 scale topographic maps were used to estimate land surface elevation for the same 500-meter grid. The difference in elevation between the two time periods was estimated to be the total depth of subsidence. The time-averaged rate of subsidence was calculated as the total amount of subsidence divided by the time interval that ranged from 60 to 72 years..

The error in the subsidence rate estimate results from the error in the elevation estimate from the topographic maps and the change in mean sea level datum from the early 1900's to 1976 to 1978. Early leveling in California used the average of tide level gauges in California for the mean sea level datum (Birdseye, 1925). The sea level datum for the 1976 to 1978 maps is the National Geodetic Vertical Datum of 1929 (NGVD-29) that was an average of mean sea level data for 21 tide stations in the United States (Ziloski and others, 1992). The error resulting from the comparison of the two datums for mean sea level was estimated by comparing the elevations for 10 benchmarks on both sets of maps. The elevations for the benchmarks for the maps published in the early 1900's were obtained from Birdseye (1925). The elevations for the same benchmarks using NGVD-29 were obtained from Joe Vukovitch, USGS, Denver.

The benchmark elevations for the maps published in the early 1900's were generally larger than the elevations using NGVD-29. The difference between the benchmark elevations for the maps published in the early 1900's and the elevations using NGVD-29 ranged from 0.008 to 0.704 feet. The average absolute difference was 0.275 feet. This difference was not accounted for in the determination of the time-averaged subsidence rates.

The error due to estimating the elevations from the contours is about one-half of the contour interval (5 feet) for the topographic maps or 2.5 feet (Joe Vukovitch, USGS, Denver, personal communication, 1996). The percent error for each subsidence rate was calculated as follows. The subsidence rate was calculated at each grid point as the difference between the elevations on the two maps plus or minus the error, divided by the time interval between the two mappings:

subsidence rate = (Elev1978 - Elev1906 +/- e)/T (B.1)

where Elev1978 is the elevation from the 1976 to 1978 USGS topographic maps,
Elev1906 is the elevation from the 1906 to 1911 USGS topographic maps,
e is the error associated with the elevation contours (1/2 the contour interval) and,
T is the time interval between the two elevation measurements.

The error was calculated as

e = E1978 + E1906 = +/- 5 feet (B.2)

where E1978 and E1906 are the errors associated with the two sets of topographic maps (E1978 = E1906 = +/- 2.5 feet).

The percent error was calculated as the absolute value of 5 feet divided by the total subsidence multiplied times 100. The percentage error in the subsidence rate is dependent on the amount of subsidence that occurred during the approximately 70 years that elapsed between the surveying for the topographic maps.

B.2 Determination of the Areal Distribution of Peat Thickness

The peat thickness was calculated on the 500-meter grid as the difference between the basal elevation of peat or peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps. Peat or peaty mud of tidal wetlands includes the organic deposits derived from decayed vegetation that formed as the result of sea level rise during the last 7,000 years. Atwater's (1982) delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soil surveys. The areal distribution of the basal elevations of the peat deposits was delineated from about 1,200 borehole logs collected through 1980.

The majority of the locations of the borehole logs were on or near the levees. The peat thickness data was compared with the delineation of organic soils or highly organic mineral soils in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993). Where there were discrepancies between the two sources of information for the extent of peat soils, the soil survey data was assumed to be correct.

B.3 Areal Variability of Soil Characteristics

The delineation of soil series as mapped in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993) were entered into the GIS developed by the Department of Water Resources Central District in digital form. The soil organic matter content was the primary soil characteristic of interest. The soil organic matter content was estimated for the 11 soil series which were either organic soils or highly organic mineral soils based on the data provided in the soil surveys. Specifically, the soil surveys for San Joaquin and Sacramento counties provided a range of values for percent soil organic matter. The midpoint of this range was assigned to that series in the GIS database. The percent organic matter for the soil series mapped in Contra Costa County was estimated from the data provided in the soil surveys for San Joaquin and Sacramento Counties.

B.4 Geographic and Hydrographic Data

Geographic and hydrographic data was obtained as USGS Digitial Line Graphs at 1:100,000 scale from the Teale Data Center.

B.5 Delineation of Priority Areas for Subsidence

The areal distribution of time-averaged subsidence rates and peat thickness was used to delineate priority areas for subsidence mitigation. The first priority area includes those lands where the time-averaged subsidence rates were greater than 1.5 inch per year and the peat thickness was greater than 10 feet. The second priority area includes lands where the time-averaged subsidence rates were greater than 1.5 inch per year and the peat thickness was less than or equal to 10 feet.

B.6 Results of Delineation of Priority Areas

Table B.1. Acreages by island for the 2 priorities for subsidence mitigation. Priority 1 includes areas where the time-averaged subsidence rate was greater than 1.5 inch per year and the peat thickness was greater than 10 feet. Priority 2 includes areas where the subsidence rate was greater than 1.5 inch per year and the peat thickness was less than or equal to 10 feet.

Priority 1		Priority 2	
Quimby	35	Quimby	35
Grand	250	Staten	144
King	70	King	1,478
Bethel	70	Brannan	1,440
Woodward	130	Bethel	350
Holland Tract	410	Tyler	610
Medford	570	Sherman	390
Rindge	600	Bradford	860
Sherman	1,480	Holland Tract	930
Empire	600	Lower Jones	2,340
McDonald	910	Bouldin	2,940
Bacon	790	Orwood	840
Jersey	670	Victoria	1,000
Bradford	710	Venice	1,270
Twitchell	1,720	Palm	1,020
Tyler	2,180	Empire	2,570
Brannan	1,700	Mandeville	2,350
Staten	1,400	Rindge	3,680
Venice	950	Webb Tract	2,400
Bouldin	1,860	Bacon	3,830
Mandeville	1,940	McDonald	4,940
Webb Tract	3,920	Woodward	310
Total	22,900	Total	35,700

B.7 Uncertainty in the Spatial Analysis

Uncertainty in the spatial analysis is the result of uncertainty in the thickness of the peat soil and the error in the estimation of the subsidence rate. The subsidence rate error is the result of errors associated with the use of topographic elevations as described above and the use of different datums for the 2 surveys for the topographic maps published in 1906 to 1911 and 1976 to 1978. In general, large errors in the subsidence rate correspond to areas of the lowest time-averaged subsidence rates. The error in the subsidence rate estimate due to the mapping error is 50 percent or less for much of the Delta. The error in the estimation of the subsidence rate generally increases approaching the periphery of the Delta. The error in the western, eastern, southern and northern edges of the Delta generally approaches or exceeds 100 percent.

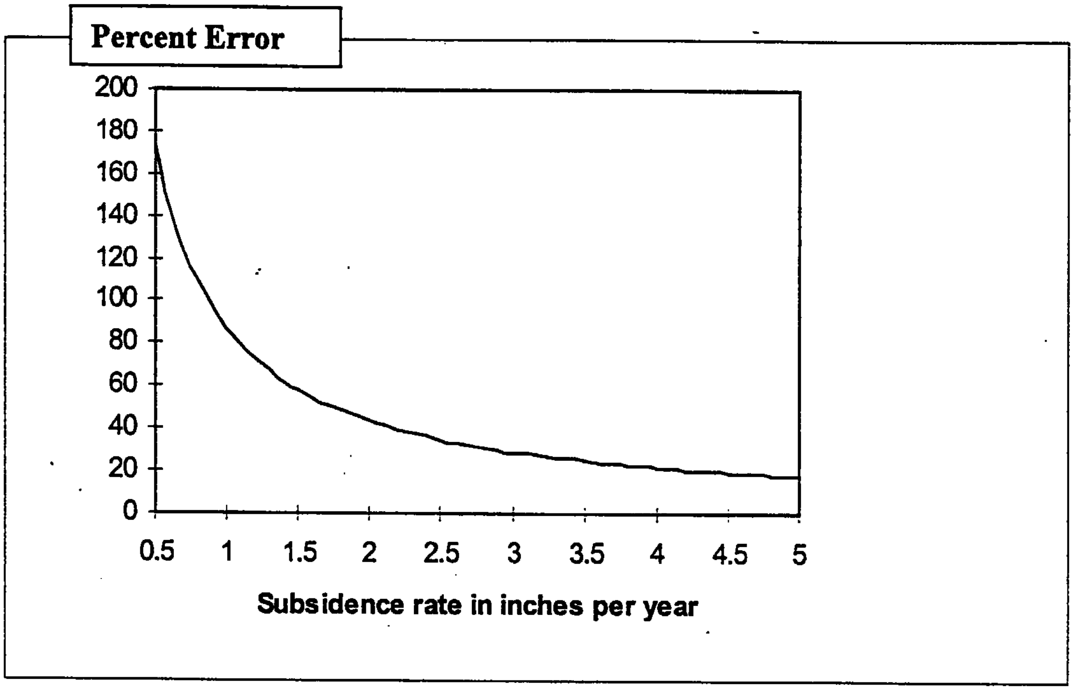
Specifically, the error in the subsidence rate on the central Delta islands, Bouldin, Island, Venice Island, Empire Tract, Mandeville Island, Bacon Island, Lower Jones Tract, McDonald Island and Empire Tract is generally less than 50 percent. Also, the error in the subsidence rates for the west-central and east-central islands, Webb Tract, Twitchell Island, Bradford Island, Rindge Tract and King Island is also generally lower than 50 percent.

Figure B.1 shows the exponential decrease in the percent error in the subsidence rate as the result of mapping errors with increasing time-averaged subsidence rates. The error was calculated for the average time between elevation measurements of 69 years for the topographic maps used in determining the total elevation change. The key questions related to the error for the purpose of determining the priority areas based on time-averaged subsidence rates are: 1) Is the distribution of subsidence rates consistent with the what is known about the distribution of present-day subsidence rates? and 2) What is the error associated with assignment of areas to one of the two categories (less than and greater than 1.5 inch per year) for subsidence rates?

The first question can be answered qualitatively based on recently collected data for subsidence for selected areas of the Delta. Specifically, data from Rojstaczer and Deverel (1995), Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) are consistent with the spatial distribution of subsidence rates presented here. Subsidence rates in the central Delta (Lower Jones Track, Bacon and Mildred islands) are greater than in the western Delta (Sherman and Jersey islands). However, subsidence has not been measured extensively throughout the Delta so that it is impossible to compare rates for all the islands. The subsidence rates in Figure 2 are generally consistent with what is known about subsidence and organic soils in the Delta (Prokopovitch, 1985). The highest soil organic matter contents and subsidence rates are in the central Delta. The soils are lower in organic matter content and subsidence rates are lower approaching the margins of the Delta

The second question can be answered based on the distribution of error for subsidence rates. Further error analysis using the data shown Figure B.1 and the distribution of error in the subsidence rate was used to determine the effect of the distribution of error on the assignment of priorities.

Figure B.1. Relation of error in the estimation of the time-averaged subsidence rate to the subsidence rate.



Using the data shown in Figure B.1 and the distribution of error in the subsidence rate, the lowest time-averaged rate of subsidence that could be erroneously classed as a rate of over 1.5 inch per year is 0.7 inch per year (the error associated with the rate of 0.7 inch per year is 122 percent). The highest time-averaged subsidence rate that could be classed under 1.5 inch per year is 2.3 inches per year (the error associated with the rate of 2.3 inches per year is 36 percent). Data for Sherman Island and Webb Tract was used to evaluate the effect of errors on the acreage within each priority area.

The data for these two islands represent the variability in the data set and the error analysis illustrates the possible range in calculated acreage in the two priority areas. About 80 percent of Sherman Island in the western Delta have peat greater than 10 feet thick but most of the time-averaged subsidence rates were below 1.5 inch per year. In contrast, Webb Tract has experienced time-averaged subsidence rates generally greater than 2.5 inches per year and about 50 percent of the island have peat soils greater than 10 feet thick. Webb Tract has the largest acreage in priority 1. The acreage in priority 1 on Sherman Island is about equal to the median. Sherman has one of the smallest acreage in priority 2.

The results of the error analysis are shown in Table B.2. The range of acreage on Webb Tract for priority 1 shows that the acreage in priority 1 could be overestimated by 54 % and underestimated by less than 1 %. For priority 2, the range in acreage on Webb Tract shows that the acreage in priority 2 could be overestimated by 24 % and underestimated by 10%. In contrast, the ranges of acreage in each priority for Sherman Island are large, ranging up to 1,000 percent. The subsidence rates for Sherman are lower than Webb and the error associated with the subsidence-rate estimate is higher and the range of acreage classified in each priority is large. The results of this analysis point to the need for additional data collection for subsidence rates in the western Delta and other areas where time-averaged subsidence rates are mapped as1.5 inch per year or less.

Table B.2. Range in acreage for each priority for Sherman Island and Webb Tract.

Island	Estimated acreage in priority 1	Range	Estimated acreage in priority 2	Range
Sherman	1,480	0 - 5,410	390	41 – 2,200
Webb	3,920	1,770 - 3,940	2,400	1,860 – 2,650

The areal distribution of the estimation error for the peat thickness was not determined. The density of borehole data and the error in the land-surface elevation primarily determines the error. The land-surface elevation error is due to leveling error in the determination of land-surface elevation that is about plus or minus 2.5 feet and the subsidence that has occurred since 1974 (about 1 to 4 feet). The total land-surface elevation error ranges from about –1.5 to 6.5 feet.

Table B.3 shows the number and average density of data points from borehole logs used to estimate the peat thickness. The data in Table B.3 does not present the entire story relative to the density of data points for peat thickness. Some data points were used for islands besides those for which they are assigned in Table B.3 since the data for peat thickness was extrapolated across channels. Also, most of the data points are on the levees so that the range of area without borehole data for each island varies substantially. In general, data densities greater than 200 acres per point result in moderate to high uncertainty in the estimation of the basal peat elevation for large areas of the islands.

Of those islands where the density of peat thickness data is greater than 200 acres per point, only 6 have acreage in the 2 priorities (Orwood Tract, Victoria Island, Brannan-Andrus Island, King Tract, Tyler Island and Grand Island). Brannan-Andrus Island, King Tract and Tyler Island have significant acreage in the 2 priority areas. Grand Island is mapped as having a large area of deep peat but has little acreage in the two priority areas because of the low time-averaged subsidence rates. Although there is uncertainty in the delineation of the priority areas for subsidence mitigation, the delineation is based on the available data and provides a starting point for further data collection efforts to better define areas for subsidence mitigation.

Table B.3. Number of data points, acreage and data density for each island used to delineate the distribution of peat thickness.

Island	Number of points	Acreage	Data density (acres/point)
Medford	31	1,219	39
Jersey	60	3,471	58
Bradford	28	2,051	73
Palm	32	2,436	76
Mandeville	68	5,300	78
Woodward	23	1,822	79
Bethel	43	3,500	81
Bacon	66	5,625	85
Sherman	105	9,937	95
Webb Tract	58	5,490	95
Twitchell	36	3,516	98
Venice	31	3,220	104
Empire	28	3,430	123
Canal Ranch	23	2,996	130
Holand	31	4,060	131
Coney	7	935	134
Bouldin	44	6,006	137
Staten	61	9,173	150
McDonald	39	6,145	158
Lower Jones	33	5,894	179
Hotchkiss	17	3,100	182
Byron	36	6,933	193
Rindge Tract	35	6,834	195
Terminous	50	10,470	209
Lower Roberts	48	10,600	221
Upper Jones	27	6,259	232
Orwood	13	4,138	318
Brack	14	4,873	348
Victoria	19	7,250	382
Brannan-Andrus	31	13,000	419
Bishop	3	2,169	723
King	4	3,260	815
New Hope	8	9,300	1,163
Tyler	7	8,583	1,226
Grand	3	17,010	5,670
Veale	0	1,298	
Shin Kee	0	1,016	
Rio Blanco	0	705	
Union	0	22,202	
Shima	0	2,394	
Ryer	0	11,880	

REFERENCES

Atwater, B.F., 1982, Geologic Maps of the Sacramento-San Joaquin Delta, US Geological Survey, Miscellaneous Field Studies Map MF - 1401

Birdseye, C.H., Spirit leveling in California, 1896-1923, US Geological Survey Bulletin 766.

Broadbent, F.E., Factors influencing the decomposition of organic soils of the California Delta, Hilgardia, 29, 587-612, 1960.

Carlton, A.B. and Schultz, H.B., 1955 to 1966, Annual Statements of Progress for Project 1686, Peat land conservation and peat dust abatement, University of California, College of Agriculture, Agricultural Experiment Station, Department of Soils and Plant Nutrition, Davis, California

Conn, E.E. and Stumpf, P.K., 1976, Outlines of biochemistry, John Wiley and Sons, New York

Cooke, J. and Colemen, D., 1973, Disaster strikes Isleton, Reclamation Era, 59, 1-9

Cosby, S.W., 1941, Soil survey of the Sacramento-San Joaquin Delta Area, California: Bureau of Plant Industry, United States Department of Agriculture, p. 1-47

Deverel, S.J.,1983, Chemical transformations as related to the oxidation-reduction potential in Central California Histosols, Ph.D. Dissertation, University of California at Davis.

Deverel, S.J. and Rojstaczer, S.A. 1996, Subsidence of agricultural lands in the Sacramento-San Joaquin Delta, California: Role of aqueous and gaseous carbon fluxes, Water Resources Research, 32, 2359-2367

Deverel, S.J., Wang, Bronwen and Rojstaczer, S.A., 1998, Subsidence in the Sacramento-San Joaquin Delta, *in* (Borchers, J.W., ed.) Proceedings of the Joseph Poland Subsidence Symposium, Association of Engineering Geologists (in press).

Department of Water Resources, 1986, Delta Subsidence Investigation Progress Report, p. 1-53.

Department of Water Resources, 1989, Delta Subsidence Investigation Progress Report, p. 1-6

Department of Water Resources, 1980, Subsidence of organic soils in the Sacramento-San Joaquin Delta, Central District, Sacramento, California

Eggelsmann, R. Heathwatie, A.L., Grosse-Brauckmann, G., Kuster, E., Nauke, W., and Schweickle, 1990, Physical processes an properties of mines in Heathwaite, A.L., and Gottlich, Kh., eds. Mire Process, Exploitation and Conservation. John Wiley and Sons, England.

Foote, Roger and Sisson, Richard, 1992, Threatened levees on Sherman Island, Proceedings on Stability and Performance of Slopes and Embankments, Geotechnical Division, ASCE, pp. 756-774.

Hanson, B.R., and Carlton, A.B., 1980, Process summary of the Delta Salinity Study, University of California, Davis, Department of Land, Air and Water Resources.

Municipal Water Quality Investigations Program, 1997, Annual Report, October 1995 – December 1996, Department of Water Resources, Division of Planning and Local Assistance, Sacramento, California.

Orang, M.N., Grismer, M.E. and Ashktorab, H., 1995, New equations estimate evapotranspiration in Delta, California Agriculture, 49, 19-22.

Prokopovitch, N.P., 1985, Subsidence of peat in California and Floridia, Bulletin of the Association of Engineering Geologists, 22,395-420.

Rojstazcer, S.A. and Deverel, S.J., 1995, Land subsidence in drained histosols and highly organic mineral soils of California Soil Science Society of America Journal, 59:1162-1167.

Rojstaczer, S.A. and Deverel, S.J., 1993, Time dependence in atmospheric carbon inputs from drainage of organic soils, Geophysical Research Letters, 20, 1383-1386.

Rojstaczer, S.A., Hamon, R.E., Deverel, S.J. and Massey, C.A., 1991, Evaluation of selected data to assess the causes of subsidence in the Sacramento-San Joaquin Delta, California, U.S. Geological Survey Open File Report 91 -193.

Stephens, J.C., L.H. Allen, and Chen, E. 1984, Organic soil subsidence in (Holzer, T.L., ed.) Man-induced Land Subsidence, Reviews in Engineering Geology, Geological Society of America, Boulder, CO.

Shlemon, R.J. and Begg, E.L., 1975, Late Quaternary Evolution of the Sacramento-San Joaquin Delta, California in Suggate, R.P and Cressel, M.M. (Eds) Quaternary Studies, Bulletin 13, The Royal Society of New Zealand, Wellington, New Zealand, pp. 259-266.

Schorthorst, C.J., 1977, Subsidence of low moor pear soil in the western Netherlands: Institute of Land and Water Management Research Technical Bulletin 102, Wageningen, The Neatherlands, p. 265-291

Schultz, H.B., Carlton, A.B. and Lory, F., 1963, Interplanting methods for wind erosion protection in San Joaquin asparagus, California Agriculture, September.

Schultz, H.B. and Carlton, A.B., 1959, Field windbreaks for row crops, California Agriculture, November.

Soil Conservation Service, 1993, Soil Survey of Sacramento County

Soil Conservation Service, 1992, Soil Survey of San Joaquin County

Soil Conservation Service, 1978, Soil Survey of Contra Costa County

Templin, W.T. and Cherry, D.E., 1997, Drainage-return, surface-water withdrawal, and land-use data for the Sacramento-San Joaquin Delta with emphasis on Twitchell Island, California, USGS Open-File Report 97-350.

Thompson, J., 1957, The settlement geography of the Sacramento-San Joaquin Delta, California, Ph.D. dissertation, Stanford University

US Army Corps of Engineers, 1992, Sacramento-San Joaquin Delta Special Study

Weir, W.W., 1950, Subsidence of peat lands of the Sacramento-San Joaquin Delta, California, Hilgardia, v. 20, p.27-56.

Zilkoski, D.B., Richards, J.H., Young, G.M., 1992, Results of the general adjustment of the North American Vertical Datum of 1988, Surveying and Land Systems, 52, 133-149